



DØnote 5028-CONF

Search for Neutral Higgs Bosons Decaying to Tau Pairs in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

The DØ Collaboration
URL <http://www-d0.fnal.gov>

A search for the production of neutral Higgs bosons Φ decaying into $\tau^+\tau^-$ final states in $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV is presented. The data, corresponding to an integrated luminosity of up to 348 pb^{-1} , were collected by the DØ experiment at the Fermilab Tevatron Collider. Since no excess compared to the expectation from standard model processes is found, limits on the production cross section times branching ratio are set. The results are combined with those obtained from the DØ search for $\Phi b(\bar{b}) \rightarrow b\bar{b}b(\bar{b})$ and are interpreted in the minimal supersymmetric standard model.

Preliminary Results for Spring 2006 Conferences

I. INTRODUCTION

Final states leading to high-mass tau lepton pairs can arise from various physics processes beyond the standard model including the production of neutral Higgs bosons (generally denoted as Φ). This is of particular interest in models with more than one Higgs doublet, where production rates for $p\bar{p} \rightarrow \Phi \rightarrow \tau\tau$ can potentially be large enough for an observation at the Fermilab Tevatron Collider. For instance, the minimal supersymmetric standard model (MSSM) [1] contains two complex Higgs doublets, leading to two neutral CP-even (h, H), one CP-odd (A), and a pair of charged (H^\pm) Higgs bosons. At tree level, the Higgs sector of the MSSM is fully specified by two parameters, generally chosen to be M_A , the mass of the CP-odd Higgs boson, and $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets. At large $\tan\beta$, the coupling of the neutral Higgs bosons to down type quarks and charged leptons is strongly enhanced, leading to sizeable cross sections. Searches for neutral MSSM Higgs bosons have been conducted at LEP [2] and at the Tevatron [3, 4]. In this note a search for $\Phi \rightarrow \tau\tau$ decays is presented. At least one of the tau leptons is required to decay leptonically, leading to final states containing $e\tau_h$, $\mu\tau_h$ and $e\mu$, where τ_h represents a hadronically decaying tau lepton.

II. DATA AND MONTE CARLO SAMPLES

The data were collected at the Fermilab Tevatron Collider between September 2002 and August 2004 at $\sqrt{s} = 1.96$ TeV and correspond to integrated luminosities of 328 pb^{-1} , 299 pb^{-1} , and 348 pb^{-1} for the $e\tau_h$, $\mu\tau_h$ and $e\mu$ final states, respectively. Final states with two electrons or two muons have a small signal to background ratio due to the small branching fraction and the large background from Z/γ^* production, and are therefore not considered.

The $e\tau_h$ and the $\mu\tau_h$ analyses rely on single electron and single muon triggers respectively, while the $e\mu$ analysis uses $e\mu$ triggers. The triggers exploit the typical signatures of leptons in the detector, including high-momentum tracks in the tracking system, energy deposits in the calorimeter, and hits in the muon detector.

Signal and standard model processes are modeled using the PYTHIA 6.202 [6] Monte Carlo (MC) generator as well as GEANT [7], which provides a detailed simulation of the detector geometry. MC events are then processed further with the same reconstruction programs as used for data. All background processes, apart from QCD multijet production, are normalized using cross sections calculated at next-to-leading order (NLO) and next-to-NLO (for Z boson, W boson, and Drell-Yan production) based on the CTEQ5 [8] parton distribution function (PDF).

The normalization and shape of background contributions from QCD multijet production, where jets are misidentified as leptons, are estimated from the data itself by using like-sign e and τ_h candidate events (in the $e\tau_h$ analysis) or by selecting background samples by inverting lepton identification criteria (in the $\mu\tau_h$ and $e\mu$ analyses). These samples are normalized to the data at an early stage of the selection in a region of phase space dominated by multijet production.

III. EVENT SELECTION

Isolated electrons are reconstructed based on their characteristic energy deposition in the calorimeter, including the transverse and longitudinal shower profile. In addition, a track must point to the energy deposition in the calorimeter, and the track momentum and calorimeter energy must be consistent. Further rejection against background from photons and jets is achieved by using a likelihood discriminant.

Muons are selected using tracks in the central tracking detector in combination with patterns of hits in the muon detector. Muons are required to be isolated in both the calorimeter and the tracker. Reconstruction efficiencies for both leptons are measured using data.

A hadronically decaying tau lepton is characterized by a narrow isolated jet with low track multiplicity. The tau reconstruction is either seeded by calorimeter energy clusters or tracks. Three τ -types are distinguished:

- τ -type 1: a single track with a calorimeter cluster without any electromagnetic subclusters (1-prong, π -like);
- τ -type 2: a single track with a calorimeter cluster and electromagnetic subclusters (1-prong, ρ -like);
- τ -type 3: two or three tracks with an invariant mass below 1.1 or 1.7 GeV, respectively (3-prong).

A set of neural networks, one for each τ -type, is developed based on further discriminating variables. The neural networks were already used for a cross section measurement of the process $Z/\gamma^* \rightarrow \tau\tau$ [9]. The input variables exploit the differences between hadronically decaying tau leptons and jets in the longitudinal and transverse shower shape as well as differences in the isolation in the calorimeter and the tracker. The training of the neural networks is performed

TABLE I: Numbers of events observed in data and expected for background and the efficiency for a signal with $M_\phi = 150$ GeV for the three analysis channels, with statistical and systematic uncertainties added in quadrature.

Analysis	$e\tau_h$	$\mu\tau_h$	$e\mu$
Data	484	575	41
QCD	199.5 \pm 26.0	62.2 \pm 6.6	2.1 \pm 0.4
$Z/\gamma^* \rightarrow \tau\tau$	202.7 \pm 26.3	491.7 \pm 52.6	39.4 \pm 5.0
$Z/\gamma^* \rightarrow ee, \mu\mu$	10.2 \pm 1.4	4.6 \pm 1.1	0.63 \pm 0.12
$W \rightarrow e\nu, \mu\nu, \tau\nu$	14.0 \pm 1.9	13.5 \pm 1.6	0.30 \pm 0.20
Di-boson (WW, WZ, ZZ)	0.54 \pm 0.09	3.05 \pm 0.33	0.99 \pm 0.14
$t\bar{t}$	0.35 \pm 0.05	1.22 \pm 0.14	0.06 \pm 0.02
Total expected	427.3 \pm 55.3	576.3 \pm 61.5	43.5 \pm 5.3
Efficiency %	4.8 \pm 0.4	8.6 \pm 0.8	4.3 \pm 0.5

using multijet events from data as the background sample and tau MC events as signal, resulting in a network output close to one for tau candidates and close to zero for background. For τ -types 1 and 2, hadronic tau candidates are required to have a neural network output greater than 0.9. Due to the larger background contamination, this cut value is tightened to 0.95 for τ -type 3.

Electrons and muons can be misidentified as one-prong hadronic tau decays. To reject electrons, it is exploited that hadronically decaying tau candidates deposit a significant fraction of their energy in the hadronic part of the calorimeter. The ratio between the transverse energy in the hadronic calorimeter and the transverse momentum of the tau track is required to be larger than 0.4. With a smaller rate, background from muons occurs in τ -types 1 and 2 in the $\mu\tau_h$ analysis. This background is suppressed by rejecting tau candidates to which a muon can be matched.

The signal is characterized by two leptons, missing transverse momentum, and little jet activity. It would stand out as an enhancement above the background from standard model processes in the visible mass

$$M_{\text{vis}} = \sqrt{(P_{\tau_1} + P_{\tau_2} + \cancel{P}_T)^2},$$

calculated using the four vectors of the visible tau decay products $P_{\tau_{1,2}}$ and of the missing momentum $\cancel{P}_T = (\cancel{E}_T, \cancel{E}_x, \cancel{E}_y, 0)$. For the optimization of the signal selection, only the high mass region is used, which is defined as $M_{\text{vis}} > 120$ GeV in the $e\tau_h$ and $\mu\tau_h$ analyses and as $M_{\text{vis}} > 110$ GeV in the $e\mu$ analysis.

In the $e\tau_h$ and $\mu\tau_h$ analyses, an isolated lepton (e, μ) and an isolated hadronic tau with transverse momenta above 14 GeV and 20 GeV respectively are required. In addition to the irreducible background from $Z/\gamma^* \rightarrow \tau\tau$ production, a $W \rightarrow \ell\nu$ decay can be misidentified as a high-mass di-tau event if it is produced in association with an energetic jet that is misidentified as a hadronic tau decay. In these events, a strongly boosted W boson recoils against the jet, and the mass of the W boson can be reconstructed in the following approximation

$$M_W^{e/\mu} = \sqrt{2 E^\nu E^{e/\mu} (1 - \cos \Delta\phi)},$$

where the azimuthal angle $\Delta\phi$ is between the lepton and the \cancel{E}_T , and $E^\nu = \cancel{E}_T \cdot E^\ell / E_T^\ell$. To suppress the large W +jet background, $M_W^{e/\mu}$ is required to be less than 20 GeV.

In the $e\mu$ analysis, two isolated leptons with $p_T > 14$ GeV are required. The dominant background contributions after the lepton selection come from the irreducible $Z/\gamma^* \rightarrow \tau\tau$ process, followed by $WW, WZ, t\bar{t}, W \rightarrow \ell\nu$, and multijet events. In this analysis the multijet background is suppressed by requiring $\cancel{E}_T > 14$ GeV. Background from W +jet events can be reduced using the transverse mass $M_T^{e/\mu} = \sqrt{2 p_T^{e/\mu} \cancel{E}_T (1 - \cos \Delta\phi)}$ by requiring that either $M_T^e < 10$ GeV or $M_T^\mu < 10$ GeV. Furthermore the minimum angle between the leptons and the \cancel{E}_T vector, $\min[\Delta\phi(e, \cancel{E}_T), \Delta\phi(\mu, \cancel{E}_T)]$ has to be smaller than 0.3. Finally, a cut on the scalar sum H_T of the transverse momenta of all jets in the event, $H_T < 70$ GeV, is applied to suppress contributions from $t\bar{t}$ background.

IV. RESULTS

The numbers of events observed in the data and those expected from the various standard model processes are summarized in Table I. The distribution of the visible mass as well as the contributions from various background components are shown in Fig. 1.

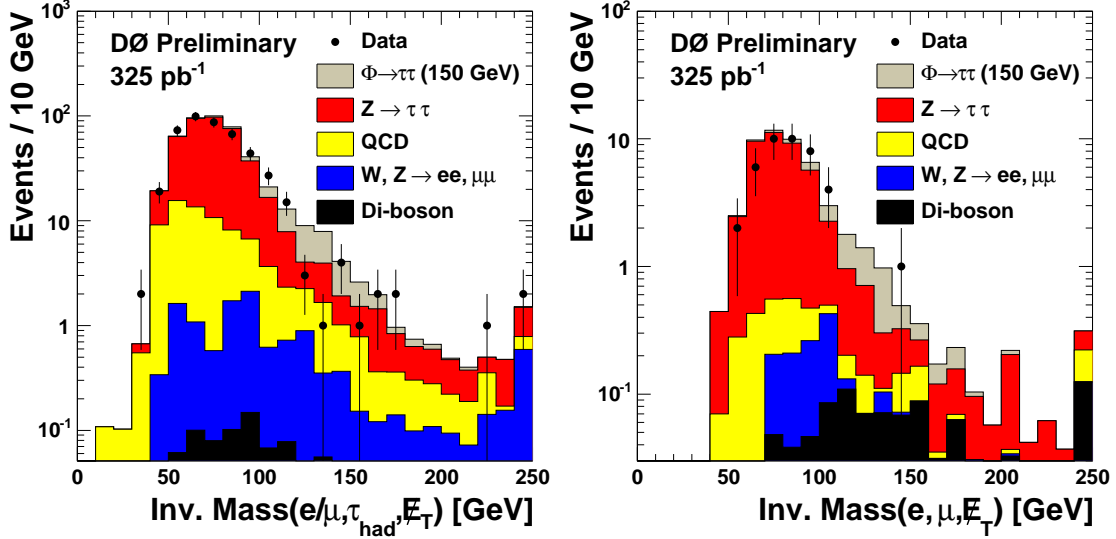


FIG. 1: The distribution of the visible mass M_{vis} for the two final states involving hadronic tau decays and for the $e\mu$ final state. The Higgs signal is normalized to the cross section excluded by this analysis.

The estimate of the expected numbers of background and signal events depend on numerous measurements that introduce a systematic uncertainty: integrated luminosity (6.5%), trigger efficiency (1%–4%), lepton identification and reconstruction efficiencies (2%–5%), jet energy calibration (2%–4%), PDF uncertainty (3%–4%), and modeling of multijet background (2%–9%). All except the last one are correlated between the three final states.

As can be seen from Table I and Fig. 1, good agreement is found between the numbers of events observed and those expected from standard model backgrounds.

The efficiencies for a Higgs boson signal are found to vary between 2.1%, 4.0%, and 1.2% for $M_\Phi = 100$ GeV and 9.9%, 13.6%, and 9.3% for $M_\Phi = 300$ GeV for the $e\tau_h$, $\mu\tau_h$, and $e\mu$ analyses respectively. Since no significant evidence for the production of neutral Higgs bosons with decays $\Phi \rightarrow \tau\tau$ is observed, upper limits on the production cross section times branching ratio are extracted as a function of M_Φ . In order to maximize the sensitivity (expected limit), the event samples of the $e\tau_h$ and $\mu\tau_h$ analyses are split into subsamples according to different signal-to-background ratios ($M_W^{e,\mu} < 6$ GeV, $6 < M_W^{e,\mu} < 20$ GeV) and τ -type. Furthermore the differences in shape between signal and background are exploited by using the information of the full mass spectrum of M_{vis} in the limit calculation. Both the expected and the observed limits on the cross section times branching ratio at the 95% confidence level (CL), calculated using the modified frequentist approach [10], are presented in Fig. 2 as a function of M_Φ .

In the MSSM, the masses and couplings of the Higgs bosons depend, in addition to $\tan\beta$ and M_A , on the SUSY parameters through radiative corrections. In a constrained model, where unification of the SU(2) and U(1) gaugino masses is assumed, the most relevant parameters are the mixing parameter X_t , the Higgs mass parameter μ , the gaugino mass term M_2 , the gluino mass m_g , and a common scalar mass M_{SUSY} . Limits on $\tan\beta$ as a function of M_A are derived for two scenarios assuming a CP-conserving Higgs sector: the so-called m_h^{max} scenario (with the parameters $M_{\text{SUSY}} = 1000$ GeV, $X_t = 2000$ GeV, $M_2 = 200$ GeV, $\mu = \pm 200$ GeV, and $m_g = 800$ GeV) and the no-mixing scenario (with the parameters $M_{\text{SUSY}} = 2000$ GeV, $X_t = 0$, $M_2 = 200$ GeV, $\mu = \pm 200$ GeV, and $m_g = 1600$ GeV) [11]. The production cross sections, widths, and branching ratios for the Higgs bosons are calculated over the mass range from 90 to 300 GeV using the FEYNHIGGS program [12], where the complete set of one-loop corrections and all known two-loop corrections are incorporated. The contributions of SUSY particles in the loop of the gluon fusion process are taken into account, as well as mass- and $\tan\beta$ -dependent decay widths. In the region of large $\tan\beta$, the A boson is nearly degenerate in mass with either the h or the H boson, and their production cross sections are added.

The D0 results obtained in the present analysis are also combined with those obtained in the $\Phi b(\bar{b}) \rightarrow b\bar{b}b(\bar{b})$ search [3], which are re-interpreted using the updated definitions of the MSSM scenarios used in this note. These limits are shown in Fig. 3. For illustration purposes, the limit is shown up to $\tan\beta = 100$, ignoring the effects from potentially large higher-order corrections in the very high $\tan\beta$ regime.

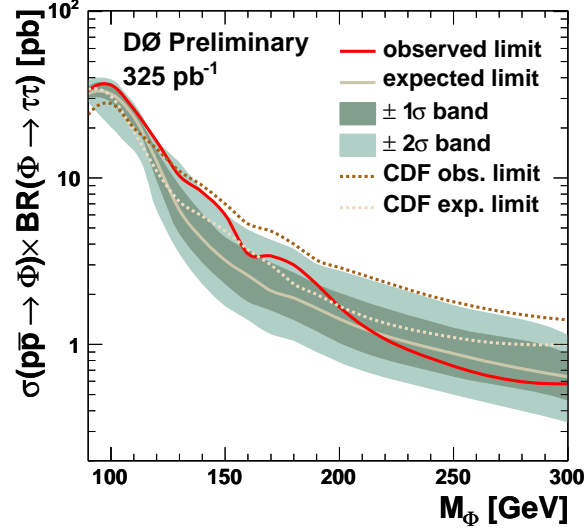


FIG. 2: The observed and expected 95% CL limits on the cross section times branching ratio for $\Phi \rightarrow \tau\tau$ production as a function of M_Φ .

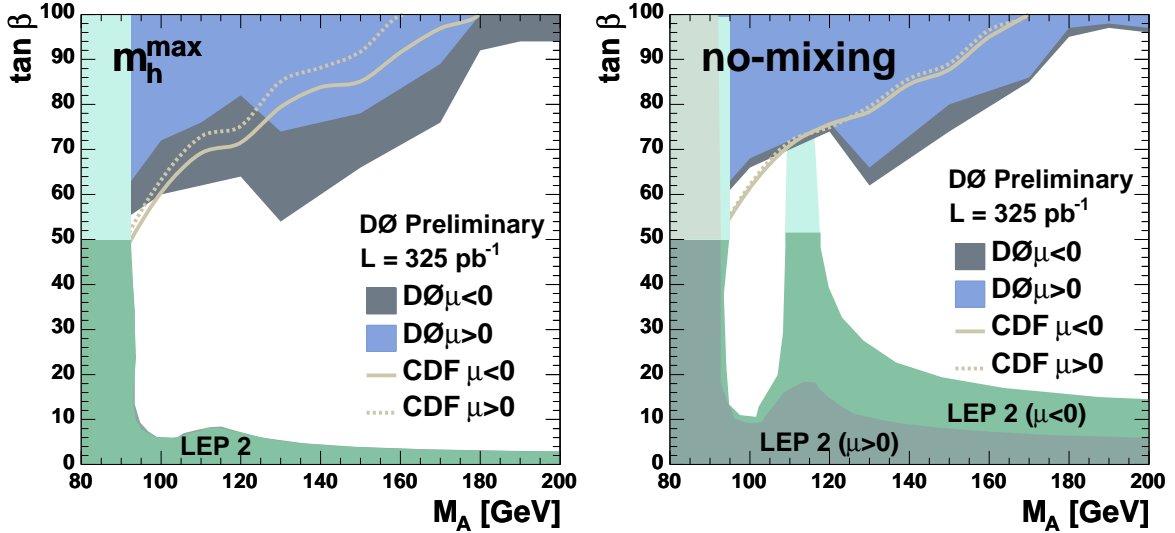


FIG. 3: Excluded region in the $(M_A, \tan \beta)$ plane for the m_h^{\max} and the no-mixing scenario for $\mu = +200$ GeV and $\mu = -200$ GeV. The results obtained in the present analysis are combined with those obtained in the $\Phi b(\bar{b}) \rightarrow \bar{b}b(b)$ search [3]. The LEP experiments only probed the region $\tan \beta < 50$.

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